Progress Toward Magnetic Suspension and Balance Systems for Large Wind Tunnels

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Recent developments and current research efforts leading toward realization of a large-scale production wind tunnel magnetic suspension and balance facility are reviewed. Progress has been made in the areas of model roll control, high-angle-of-attack testing, digital system control, calibration techniques, high magnetic moment superconducting solenoid model cores, and system failure tolerance. Formal design studies have confirmed the engineering feasibility of large-scale facilities.

Nomenclature

F = model magnetic force
H = magnetic field strength (A m^{-1})
I_D = current density (A m^{-2})
M = model magnetization (A m^{-1})
T = model magnetic torque
μ_0 = permeability of free space ($4\pi \times 10^{-7}$ Hm^{-1})

Introduction

SINCE the first demonstrations of a practical wind tunnel magnetic suspension and balance system (MSBS), over 25 years ago, considerable research efforts at a number of institutions[1] have been devoted to advancing the technology of MSBSs to a level where application to everyday wind tunnel testing of aircraft models would be practical.

This goal is nearing realization and the following sections summarize some relatively recent developments in a NASA (Langley Research Center) program aimed toward development of the technology required for large-scale MSBS facilities.

The author was initially involved in this research (1978-1983) via a NASA-funded program at the University of Southampton, England, and several of the developments outlined herein have been made at that institution. Current affiliation has permitted closer involvement with other NASA-sponsored MSBS activities and these are reviewed later.

The initial driver prompting work on MSBSs was the complete elimination of model support interference (Fig. 1). This remains the prime objective particularly since the new generations of high Reynolds number wind tunnels, considered essential for testing up to transonic speeds, will be operated at high dynamic pressures, consequently employing relatively massive model support systems.

However, there exist many other potential advantages of MSBSs, including:

1) High-angle-of-attack or extreme attitude testing. Free from mechanical restraint, arbitrary model positions and attitudes may be rapidly selected.

2) Dynamic testing. Following item 1 above, arbitrary model motions are easily created. Further, real-time whole body aerodynamic force and torque data are always available.

3) High productivity. Following items 1 and 2 above, a wide variety of tests may be performed concurrently with the same model and test setup.

At the beginning of the current phase of research, there existed numerous fundamental technical problems to be resolved before construction of a large-scale production facility could be attempted. Substantial progress has been made in a number of areas, each of which will be addressed in turn.

Recent Advances

Roll Control

During testing of winged models, particularly at high angles of attack or substantially yawed, powerful aerodynamic roll torques are likely to be generated. These must normally be offset magnetically and there had been serious concern that lack of adequate magnetic roll torque capability would represent a block to future MSBS development. A relatively new scheme of magnetic roll torque generation, referred to as the spanwise magnet scheme, illustrated in Fig. 2, appears to offer a solution.[2]

The spanwise permanent magnet variant has been demonstrated experimentally in the University of Southampton's MSBS with magnetic roll torque capability considerably exceeding that available from previous roll control systems used therein. For application to large-scale facilities, the alternative variant, spanwise iron magnets, promises greater torque capability. Unfortunately, this variant cannot be demonstrated properly with the University of Southampton's MSBS due to its relatively weak electromagnet capacity and inappropriate configuration, but extensive computations of performance have been carried out, backed by analytic and experimental verification, using a sophisticated but well-proven finite element computer program, GFUN.

A variety of configurations were studied,[2] and Fig. 3 presents some important results concerning a magnetic core geometry representative of an F-16 model, sized for an 8-ft wind tunnel test section. This forms a challenging case for this type of roll control scheme since the wing volume available for magnetic cores is very limited. The torque requirement cited in Fig. 3 corresponds to that being considered in current large MSBS design studies[3,4] and is intended to satisfy requirements for testing in unpressurized wind tunnels up to transonic Mach numbers. Torque capability appears limited principally by available electromagnet technology, the latter being difficult to assess, although the point indicated in Fig. 3 is realistic insofar as peak magnetic fields around the electromagnets remain reasonable (≃6 tesla).

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High Angle-of-Attack/Extreme Attitude Testing

Previously MSBSs have not been capable of suspending conventional models with the major axis of the model (fuselage axis) more than perhaps 30 deg displaced from the wind tunnel axis.[5] If larger excursions are required, the following fundamental problems arise:

1) Gross variation of the magnetic couplings between the electromagnets and the model.

2) Provision of accurate and wide-ranging model position/attitude sensors.

Analysis and experiment have now shown that manifestations of Problem 1 above can be accommodated in straightforward fashion. With wind tunnel (MSBS) and model axes defined in Fig. 4 and transformation matrices for yaw Ψ, pitch Θ, and roll Φ defined conventionally, the relationships between field or field gradient components, hence forces and moments, in model axes and applied field and field gradient components in MSBS axes are resolved:

$$H' = AH \tag{1a}$$

where $A = \bar{\Phi}\bar{\Theta}\bar{\Psi}$

$$\nabla' H' = A \nabla A H \tag{1b}$$

$$F' = \mu_0 \int_v M' . \nabla' H' \mathrm{d}V \tag{1c}$$

$$T' = \mu_0 \int_v M' \times H' \times r' \times (M' . \nabla' H')\mathrm{d}V \tag{1d}$$

With conventional axial ($M_{x'}$) model magnetization, it is easily deduced from Eqs. (1) that all primary free-space field or field gradient components (H_x, H_y, H_z, H_{xx}, H_{xy}, H_{xz}, H_{yy}, H_{yz}) are required independently around the origin of axes for full control at all attitudes to be possible. Further, if the applied field or field gradient components remain fairly uniform over the volume of the model core (a reasonable assumption where the model core is small with respect to the suspension electromagnets), then Eqs. (1) can be used to deduce combinations of applied fields (in MSBS axes) that will produce required independent force and torque components in model axes.

The University of Southampton's MSBS is incapable, in its normal configuration, of usefully generating one field gradient component (H_{yz}), therefore it is not able to realistically demonstrate unlimited attitude capability. However, study of Eqs. (1) supported by extensive numerical computations of a simplified geometry representative of this system[2] indicated that suspension up to at least 60-deg angle of attack was possible before the lack of H_{yz} became an embarrassment (falling sideforce capability). An axisymmetric model was thus successfully suspended over this range of angle of attack (Fig. 5) with the model control system decoupled into model axes using the computed coupling data, although that data differed only in detail from direct application of Eqs. (1).

It is concluded that operation of appropriately configured and equipped MSBSs over unlimited ranges of model attitude with full six component control is entirely practical.

Reliability

Since the consequences of loss of model control in a large MSBS are potentially so destructive, such systems will be configured and operated so as to achieve very highly reliable suspension. Previously it had been felt that the levels of hardware redundancy required in the array of electromagnets and power supplies might represent an unacceptable cost burden. It has now been argued that, provided certain unique characteristics of MSBSs are fully exploited, such as the natural presence of a relatively large number of independent electromagnets and associated power supplies, the quantity of redundant hardware, hence the cost overhead, can be quite modest—perhaps less than 20% in realistic designs.[2] Indeed,

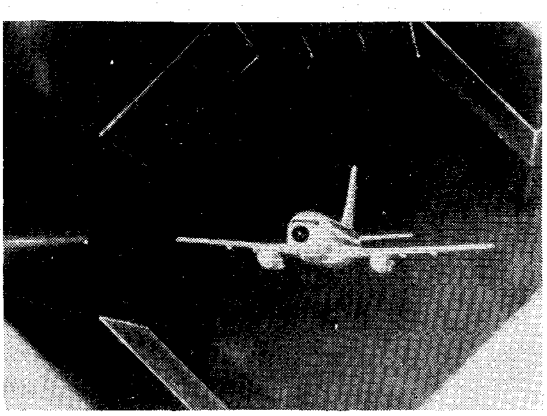


Fig. 1 Demonstration model in suspension (Southampton).

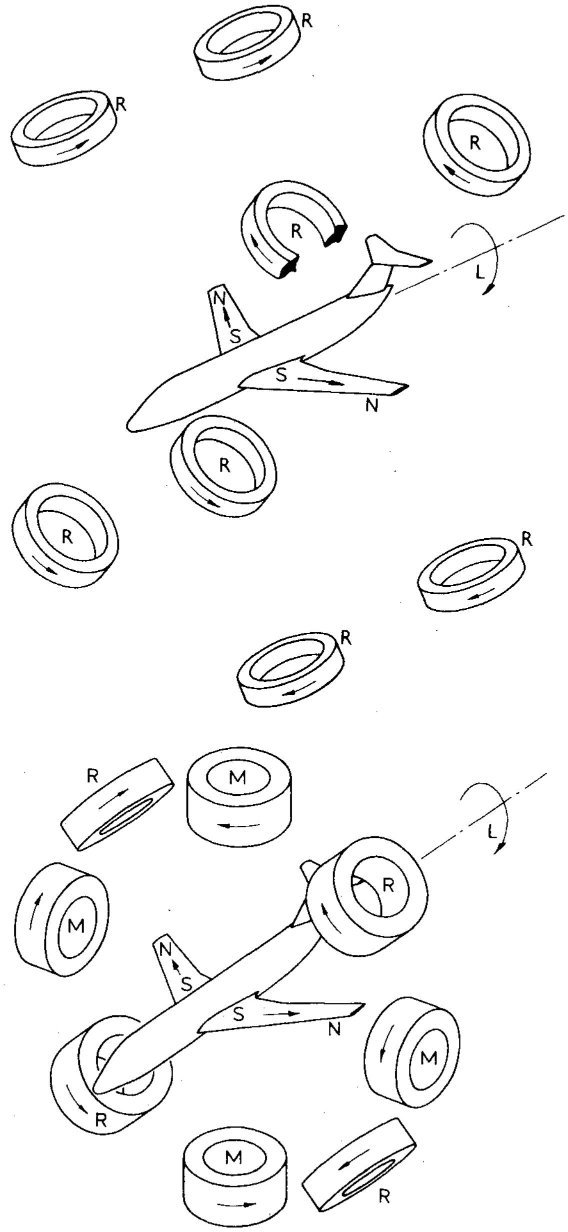


Fig. 2 Spanwise magnet roll torque generation: permanent magnets (top), iron magnets (bottom). (Electromagnets M magnetize wing cores, R produce torque).

demonstrations have shown that the University of Southampton's MSBS, without any *deliberate* inclusion of redundancy, can survive serious (simulated) hardware failures, such as the loss of power in a complete electromagnet, without loss of model control.

Control Systems and Power Supplies

Partly in order to expedite the abovementioned work, the University of Southampton's MSBS hardware has been revised extensively over the last few years and many novel features relevant to the design of large MSBSs have been inporated.[2] The entire model control system is implemented digitally, using a PDP 11/34 minicomputer (Fig. 6). At present, this controller represents merely a digital simulation of previous analog controllers, employing identical control algorithms. Thus, quantitative performance is no better than has been achieved previously, but it is anticipated that as new control algorithms become available, this performance should improve rapidly. The qualitative performance represents a quantum leap from previous analog controllers, accommodation of different model characteristics, suspension at high angles of attack, synthesis of complex model motions, preprogramming of test attitude and motion sequences, and real-time automated data acquisition all proving straightforward. Modern high-efficiency, four-quadrant, transistor switching power controllers supply current to the electromagnets, and feature the ability to regenerate reactive load power components, in this case on to internal storage capacitors. Since very high reactive powers will be encountered at large physical scales, the steady-state power consumption of the obligatory superconducting electromagnets being essentially zero of course, energy storage and regeneration are seen as essential for an economical facility.

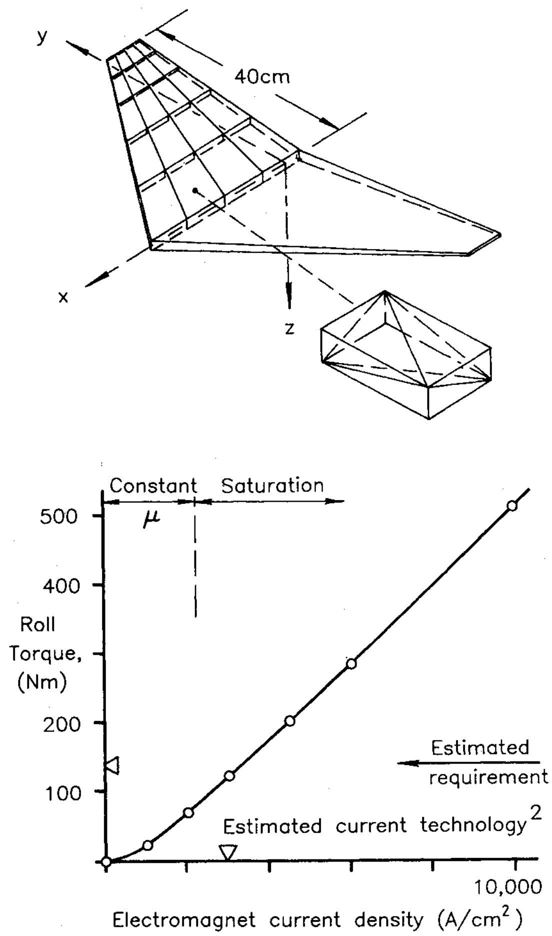


Fig. 3 Some calculated torque capabilities for spanwise iron magnets (F-16 core, Ref. 2).

Superconducting Solenoid Model Cores

For fixed overall configuration and magnetic force and torque requirements, the sizes of the suspension electromagnets and associated power supplies vary as inverse powers of the model core magnetic moment. Since the cost of a large MSBS appears to be dominated by the electromagnet and power sup-

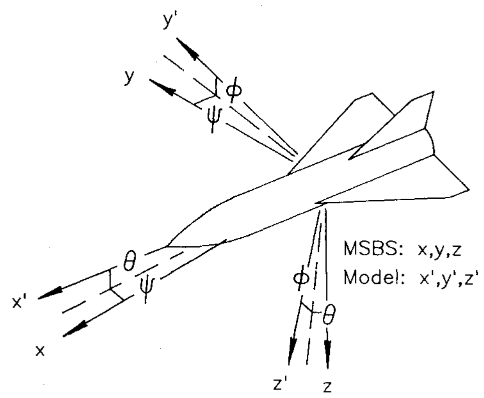


Fig. 4 Model and tunnel axis systems.

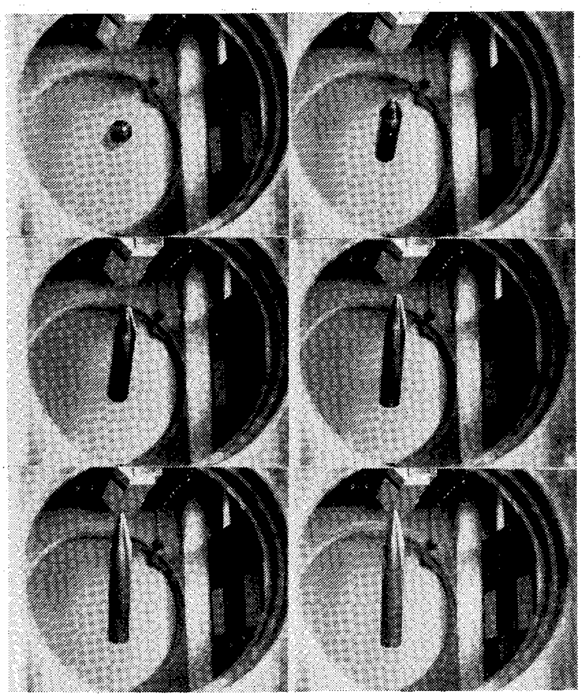


Fig. 5 Axisymmetric model at 0-60 deg angles of attack (Southampton, view through MSBS, test section removed).

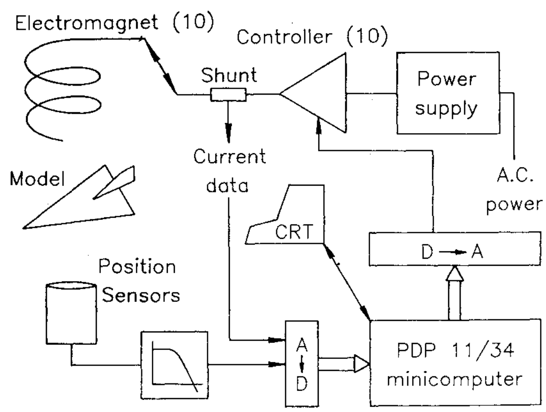


Fig. 6 Southampton MSBS hardware configuration [30 cm LaRC (AEDC) similar].

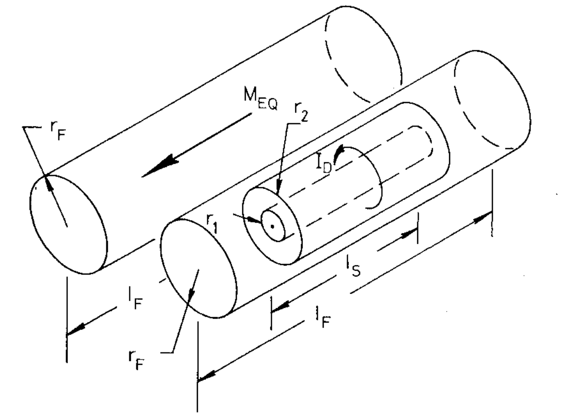


Fig. 7 Equivalent ferromagnetic and superconducting solenoid model cores.

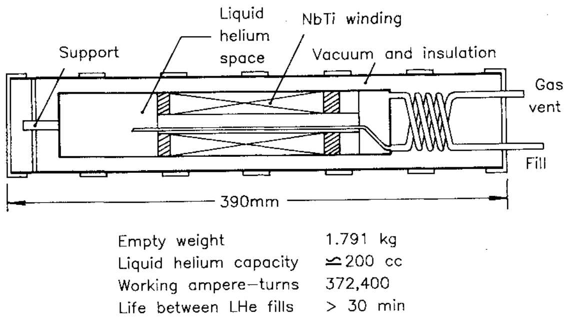


Fig. 8 Schematic cross section of experimental superconducting solenoid model core.

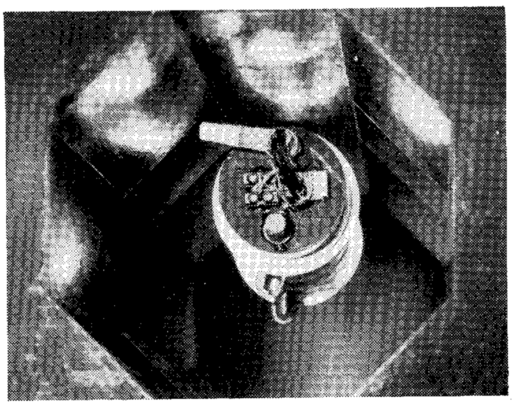
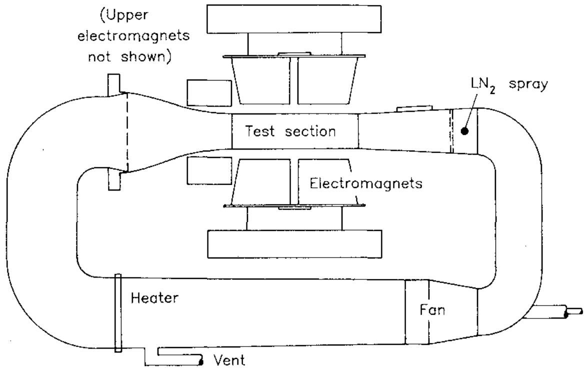


Fig. 9 Superconducting solenoid model in suspension.

ply cost, it is clearly worthwhile to strive for the highest possible model magnetic moments. Soft iron cores, magnetized by external fields, are known to be superior to the permanent magnet cores used in the University of Southampton's MSBS, saturation inductions of around 2.4 tesla being achievable (vanadium permendur[3]), with perhaps half that value for conventional permanent magnets. Recently, it was proposed that a persistent superconducting solenoid installed within the model could be similarly superior to iron. Comparing two cores of equal magnetic moment, after Fig. 7, it can be shown in a straightforward manner that

$$M_{EQ} = \frac{I_D(r_2^3 - r_1^3)l_s}{3l_F r_F^2} \qquad (2)$$

Equation (2) illustrates that M_{EQ} is expected to rise naturally with increasing scale, this trend strengthened by the fact that



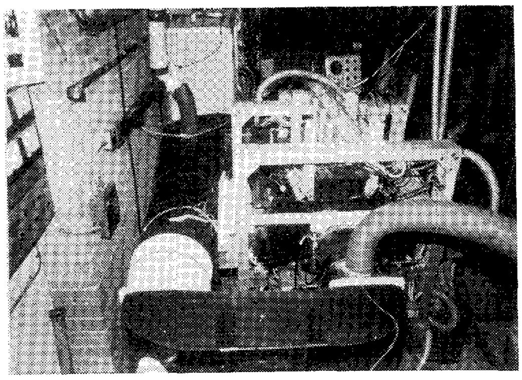


Fig. 10 Southampton MSBS/cryotunnel facility, c. 1979.

required thickness of thermal insulation $(r_F - r_2)$ remains fairly independent of scale.

In order to demonstrate the feasibility of this model core concept, a demonstration model was designed and constructed by the Institute of Cryogenics, University of Southampton,[6] with principal characteristics detailed in Fig. 8. Operating procedure for this type of model is to cool the solenoid (internally) to liquid helium temperature, fill with liquid helium, charge the solenoid to its operating current, and detach all fill/vent tubes and current or instrumentation leads, the model now being ready to suspend. Heat soak into the liquid helium environment causes slow continuous boiloff and, in the present design, boiloff gas is merely vented from one end of the dewar (around 60 ml STP gas/s). Alternative arrangements are presumed possible.

Suspension in the University of Southampton's MSBS proved very straightforward (Fig. 9) and limited force and torque calibration and helium boiloff measurements were made, summarized elsewhere.[7,8]

Design studies of superconducting solenoid models are continuing, with emphasis on larger scale and higher force capability, necessitating more complex internal design. The provision of some means of roll torque generation, for those models without wings, is also being studied, such as by inclusion of extra nonsolenoidal superconducting windings.

Calibration and Data Acquisition Techniques

With conventional means of extracting aerodynamic data, that is by monitoring of electromagnet currents, the problem of calibrating the MSBS efficiently, particularly when operating over a wide range of model attitudes, can become severe. All conventional techniques, such as application of loads to the model or direct measurement of magnetic forces and moments via a sting-mounted strain gage balance tend to be very time consuming. A new technique, dynamic calibration, has been explored briefly and may offer a rapid semiautomatic method. Here the model is deliberately oscillated by demanding ac components of suspension electromagnet current, these components then being compared with the resulting model trajectory. Provided the model's mass and moments of inertia are accurately known, the required calibration constants can be deduced.

Development of an onboard strain gage balance system with a miniaturized data telemetry package, monitoring the loads between the magnetic core and the aerodynamic shell of the model, is also underway and may prove to be a viable alternative data acquisition technique, completely avoiding the requirement for calibrating suspension electromagnet currents.

Cryogenic Wind Tunnels and MSBS

The long-term future of MSBSs undoubtedly lies with cryogenic wind tunnels, since that type of tunnel offers high Reynolds number capability in facilities of modest physical size and dynamic pressures, leading to acceptably low model loads. The compatibility of MSBSs and cryogenic tunnels has, of course, been confirmed experimentally by combining the University of Southampton's MSBS and 0.1-m low-speed cryogenic wind tunnel,[9,10] illustrated in Fig. 10.

Present Activity

Two MSBSs have been acquired by NASA Langley Research Center (LaRC) and will form the focus of experimental activity in the near term.

30 cm (In Process of Acquisition from AEDC)

The AEDC/NASA LaRC system is the largest constructed to date[1,11] intended for wind tunnels up to 33-cm test section size. During 1979-1980, the system was relocated to LaRC and reactivated in its original form with installation into a 30-cm low-speed wind tunnel completed in early 1984, as shown in Fig. 11.

Some hardware improvements have already been made, including installation of a digital control system and optical model position sensors, based on self-scanning photodiode arrays. In the medium term additional improvements are envisaged, such as upgrading of suspension electromagnets and power supplies and further refinement of the position sensing system.

Experimental utilization will be concentrated in the short term in the following areas:

1) Exploratory testing of various aerodynamic configurations.

2) Study of whole body aerodynamic data acquisition techniques.

3) Development of onboard model instrumentation and remote telemetry.

15 cm (Acquired from MIT Aerophysics Laboratory)

The MIT/NASA LaRC system is one of the most sophisticated MSBSs constructed to date,[12] featuring a relatively complex fully symmetric electromagnet array and electromagnetic model position sensing (EPS) (Fig. 12). Recommissioning at LaRC was completed in mid-1984, and research activity is now likely to concentrate on:

1) The study of position sensing systems, including the installed EPS.

2) The development of instrumentation and data acquisition techniques.

Although extensive aerodynamic testing has been performed in the past with this system, mostly using a low-speed wind tunnel also relocated to LaRC,[5] it is believed that the full magnetic force and torque capability has not yet been realized, principally due to the lack of modern high-capacity power amplifiers. Subject to improvements in this area and incorporation of more sophisticated (digital) controllers, this system may form a powerful aerodynamic test facility in its own right.

Large MSBS Design Studies

A comprehensive design study encompassing facilities sized for 4-and 8-ft test section wind tunnels was undertaken (Fig. 13) for NASA LaRC in 1981.[3] This study concluded that such systems were practical with then-existing technology although the specific designs produced appeared prohibitively costly for various reasons. However, those areas inviting technical

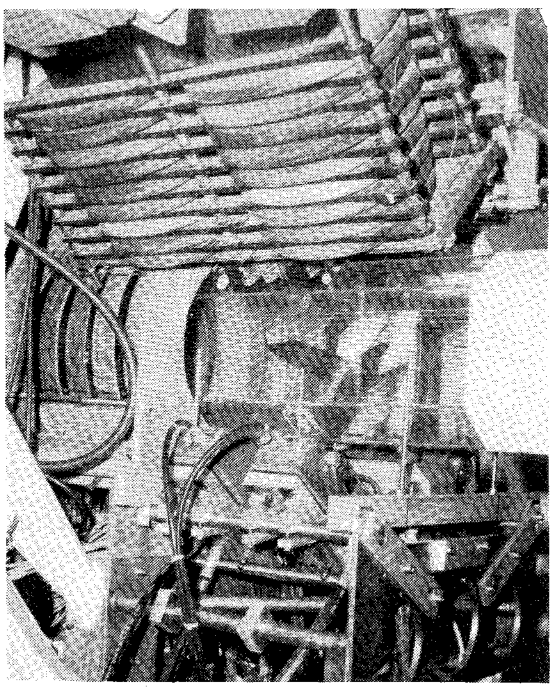


Fig. 11 30-cm LaRC (AEDC) MSBS; original configuration (optical position sensors now installed, X-ray shown).

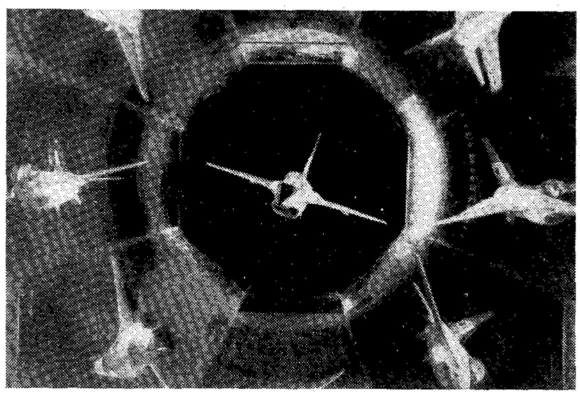


Fig. 12 15-cm LaRC (ex-MIT) MSBS; at MIT.

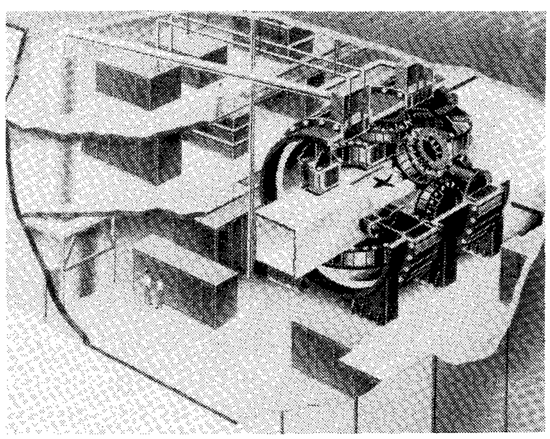


Fig. 13 General Electric Co. 8-ft MSBS design.

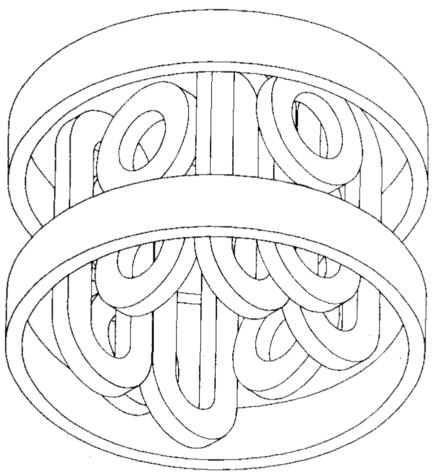


Fig. 14 Madison Magnetics Inc. 8-ft MSBS electromagnet configuration.

development were clearly identified, including incorporation of higher overall current densities in the suspension electromagnets, development of more energy-efficient power supply systems, and general configuration optimization. The ac operation of suspension electromagnets proved to be a major cost and technology driver.

A follow-up study,[4] restricted to an 8-ft wind tunnel design, was initiated in late 1983 intended to address some of the above mentioned points. The updated system design (Fig. 14) promises dramatic reductions in projected cost, with the following technical changes being most notable:

1) Exploitation of the superconducting solenoid model core concept (70% higher model magnetic moment than previous ferromagnetic core configurations).

2) Mounting of all electromagnets in a large single dewar with all-cold intermagnet structure.

3) Reconfiguration of the "roll" electromagnets and wing core arrangement.

Other Work

For many years, Oxford University, England, has been using their small MSBS for testing bodies of revolution in low-density hypersonic flow,[13] and are likely to continue.

The Future

Missing Technology

Weaknesses appear to exist in certain currently available hardware technologies, including:

1) Large, high-field, ac-capable superconducting electromagnets.

2) Very high capacity, energy-efficient power amplifiers.

3) Wide ranging, accurate, and versatile model position sensors.

It may be assumed that activity in other branches of engineering, such as power generation, transmission, and storage or robotics, etc., will result in steady development in the abovementioned areas with or without direct MSBS-related effort.

Design or operating concepts also fall short in some areas:

1) Proven rapid system calibration procedures.

2) Adaptive system control algorithms.

3) Dynamic aerodynamic data acquisition techniques.

These areas, as mentioned earlier, are currently receiving attention and are unlikely to represent fundamental blocks to MSBS development. The technical outlook for large MSBSs is thus considered good. The precise niche in the wide spectrum of aerodynamic testing that can best be filled remains to be resolved, but that a large MSBS would represent a powerful, versatile, and productive test facility is not in question.

Acknowledgments

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